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Missile Design for the Effects of Winds Aloft

13 SEPTEMBER 1962

Prepared by
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Prepared for DEPUTY COMMANDER AEROSPACE SYSTEMS
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
Inglewood, California

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ABSTRACT

A major problem in the design of large booster missiles is the proper consideration of the effects from winds aloft. Since wind magnitude and direction are statistical in nature, the problem can only be solved by the use of statistical techniques.

This report suggests that the design requirement be a given probability of failure or launch delay due to winds aloft, or an optimization between cost (in terms of weight, schedules, etc.) and the probability of failure or launch delay. A methodology is then presented, along with pertinent background information and discussion, for designing to any of those requirements. Also presented is a procedure for a prelaunch wind check in which wind effects magnitudes are predicted for a flight.

ACKNOWLEDGEMENTS

The contributions of M. D. Schwartz to this report were invaluable and are gratefully acknowledged. Important contributions were also provided by J. D. Graham, R. L. Glasser and R. H. Herndon.

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1.0 INTRODUCTION

The problem of designing a large ground launched booster missile for the effects resulting from winds aloft (the effects of ground winds will not be considered) is an important and current problem in the missile field. Its importance is a result of the fact that, when a boost vehicle climbs through the atmosphere, winds can produce effects of sufficient magnitude to effectively "design" the vehicle in some areas. In other words, some areas of the overall missile system would not require as great a capability if it were not for winds aloft. It is possible to design a missile to withstand a wind criteria so severe that it will essentially never fail due to winds. However, by applying such overconservatism to the design of a booster for space vehicles, the required booster capabilities may be seriously increased or the payload carrying capability seriously decreased.

The solution to this design problem requires the use of statistical techniques because the wind magnitude and velocity are statistical in nature. The various design requirements that this report considers are (1) a given probability of failure due to winds aloft, (2) a given probability of launch delay, if a launch is to be permitted only when the predicted wind effects are allowable; or (3) an optimum trade-off between cost (in terms of weight, complexity, etc.) and probability of failure or launch delay.

The solution provided in this report is a methodology which computes the probability of failure or launch delay for any given design. Therefore, to find a design that meets the given probability requirements, or to optimize the design, a cut-and-try process is required. The methodology could be termed an engineering approach - that is, it utilizes a number of assumptions in order to maintain practicality. These assumptions are presently necessary because they simplify computations, and because much of the statistical data used is limited in both quantity and accuracy. Efforts are being made to obtain better data, but major improvements will take years. The most unique aspect of the methodology is that it considers the combined effects of all random factors that can lead to failure (i.e., wind profiles, gusts, buffeting, in-spec missile parameter variations, etc.)

Some background information on winds, and a discussion of some current design techniques, will be provided to aid in understanding the methodology and placing it in perspective. Presentation of the methodology will

be more graphical than mathematical. This will hopefully increase clarity, although at an admitted sacrifice of mathematical rigor. Relevant information regarding design techniques for an unsymmetrical vehicle, and a prelaunch wind check procedure are placed in the Appendix to avoid a break in continuity.

2.0 BACKGROUND INFORMATION ON WINDS

Information regarding wind velocity versus altitude is divided into two parts which will be termed the wind profile, and the profile detail. The reason for this dichotomy is that balloon soundings have been used to obtain the greatest mass of wind data; and since a standard balloon sounding produces average wind velocities over altitude layers of 2000 feet, these soundings do not produce complete data on gusts and shears. The wind information produced by a balloon sounding will therefore be termed wind profile, and that undetected by the balloon sounding will be termed profile detail. These are discussed separately. The concept of a wind rose is also discussed, since it is often encountered in wind studies and criteria.

2.1 Wind Profile

A typical wind velocity profile is shown in Figure 1. It can be termed "typical" because the velocity peaks in the altitude region where high winds are most probable. Actually, winds tend to peak again in the region of 200,000 feet, but air density there is so low that the wind effects on the missile are not normally important. To provide the reader with a "feel" for wind speeds: In the region of 35,000 feet at Cape Canaveral a wind velocity of 250 ft/sec (170 mph) is exceeded about 5 percent of the time during the month of the heaviest winds.

Unfortunately, the region of high winds is also the region in which most missiles experience the highest dynamic pressure, q*, even without winds. Thus, this region usually contains the critical altitude - that is, the altitude at which the probability of failure due to winds is greatest.

The magnitude of the effects caused by winds are a function of the history of the wind shears (the rate of change of velocity with altitude) and direction, as well as instantaneous wind velocity. A change in any of these parameters will change the magnitude history of the wind effects. Therefore, the only accurate way of computing the maximum wind effect magnitudes due to any given profile is to essentially simulate the flight of the missile through that profile.

2.2 Profile Detail

As previously explained, the profile detail consists of variations in wind velocity versus altitude that cannot be detected by a balloon sounding (See Figure 1). How much of this detail is shear and how much can be termed gusts is an academic question for the purpose of this report.

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*$q = \frac{1}{2} \rho V^2$, where ρ is air density and V is velocity relative to the air mass.

The importance of the profile detail is that it produces almost all of the dynamic effects (e.g., dynamic rigid and flexible body bending moments) as opposed to the quasi-steady state effects produced by wind profiles. Unfortunately, although the effects of the profile detail can be very significant, little useful and reliable statistical data presently exists regarding profile detail. The data that is available was obtained from acceleration instrumentation on aircraft during level flight. (7) This is, therefore, gust data and does not include shear effects that are not measured by a balloon, but will be encountered by a vertically rising missile.

2.3 Wind Rose

A wind rose is not used in this report, but an understanding of it is important because it involves several concepts commonly used in wind studies and wind criteria. A typical rose of magnitude and one of direction are shown in Figure 2.

The rose of Figure 2a plots wind magnitude versus compass direction at some altitude. The magnitude in each direction is usually the wind velocity that is equaled or exceeded some percent of the time assuming that the wind is in that direction. For example, one could find the 1 percent (probability of exceedance = 1 percent) wind velocity in a compass sector by considering all the winds in that sector at the altitude of interest, and computing the wind velocity that was equaled or exceeded 1 percent of the time. By doing this in each sector, a 1 percent magnitude rose can be constructed. One could also construct a magnitude rose by plotting the magnitude of wind component exceeded in each direction some percent of the time. The probability distribution of such a wind component magnitude in a given direction is found by breaking all wind vectors down into two components, one of which is in the given direction. This wind component rose would be of a different shape and have a different meaning than the previous rose where only total wind vectors were considered.

The rose of Figure 2b plots the probability of wind occurrence versus compass direction at some altitude. The distance from the origin to any point on the rose allows one to compute the probability of the wind occurring in any sector of the compass.

3.0 DEFINITION OF TERMS

A number of important terms are used in this report. The terms wind profile and profile detail were defined in Section 2. Others of equal importance are defined below.

3.1 Wind Profile Effects And Effect Parameters

When a booster missile climbs through the atmosphere, the presence of a wind profile will cause a change (normally an increase) in aerodynamic forces on the missile. These forces produce a number of effects that will be termed wind profile effects. The most important of these effects to the present day designer are listed below along with some of the effect parameters.

(1) Structural Loads

Effect parameters are: bending moment, etc.

(2) Control System Perturbations

Effect parameters are: thrust vector angle (that is, angle from effective null), integrated thrust vector angle (important for secondary injection thrust vector control), autopilot signals (e.g., gyro outputs), etc.

(3) Trajectory Perturbations

Effect parameters are: velocity vector, missile position, dynamic pressure, angle-of-attack, etc. Many of particular interest at staging or at guidance initiation.

3.2 Non-Wind Profile Effects and Factors

The effects of wind profiles were discussed above and some effect parameters were listed. These same effects can result from factors other than a wind profile, and the same parameters will be influenced. When these effects are caused by factors other than wind profiles, they will be termed non-wind profile effects. Some of the important non-wind profile factors that must usually be considered are:

(1) Profile Detail

Profile detail produces aerodynamic loads just as the wind profile does. However, its statistics are separately defined. Also, it tends to produce dynamics, while a wind profile changes so slowly that its effects are mainly quasi-steady state. The most important effect from profile detail is usually structural loads.

(2) Buffeting

Like profile detail, buffeting produces relatively rapid variations of aerodynamic loads with structural loads constituting the main effect.

(3) Propellant Sloshing

It will produce control system perturbations and structural loads.

(4) No-Wind Trajectory Perturbations

These result from variations (within specifications) of missile parameters such as thrust, pitch program commands, gyro drift, etc. They can produce aerodynamic loads and, as a result, all of the wind profile effects listed in Section 3.1.

Non-wind profile effects are important because the failure of a missile due to winds occurs when the magnitude of some effect parameter exceeds

its design allowable, and the magnitude of the parameter may be influenced by many factors. Thus, the computation of a probability of failure requires consideration of uncertainties due to all factors, both wind profile and non-wind profile.

The design procedures presented in this report use the artificial division of wind profile effects and non-wind effects when considering the magnitude of any effect parameter. The main reason for this is that wind profile effects are usually dominant and can be computed with much more accuracy than can non-wind profile effects.

3.3 Design Allowable

A design allowable is the magnitude of a missile system design parameter which is considered to constitute a flight failure when exceeded in flight.

3.4 Probability of Failure Due to Winds

The probability of failure due to winds aloft as used in this report will mean the probability that the magnitude of an effect parameter (see 3.2) will exceed its design allowable due to all factors when (1) all parts of the missile meet specifications, and (2) the missile is launched at a random time, within a defined period of the year, and from a given location.

3.5 Launch Allowables

The launching of large boosters carrying space vehicles are usually permitted only when the magnitudes of effect parameters that are predicted for the flight are below preassigned values. These preassigned values are termed launch allowables and are usually provided as a function of time-of-flight.

3.6 Probability of Launch Delay

The probability of launch delay due to winds aloft will mean the probability that a predicted magnitude of the effect parameters will exceed its launch allowable at some time-of-flight when (1) the launch is scheduled to occur at a random time, during a defined period of the year, and from a given location, and (2) the launch delay decision is always made at a given point in the countdown.

3.7 Probability of Exceedance

The probability of exceedance is the probability that a certain magnitude will be equalled or exceeded.

4.0 DESIGN REQUIREMENTS

When the designer is given the problem of designing a new missile, he must be given some requirements in regard to the effects of winds aloft. These requirements could specify (1) a probability of success in flying through winds when a launch is made without any consideration of winds, or

(2) a probability of launching only when prelaunch checks show that the probability of failure will be less than some preassigned value. On the other hand, the requirements could specify that the designer perform an optimization in the form of a trade-off between cost (in terms of money, development time, reliability, weight, etc.) and the probability of failure or launch delay. These requirements are meaningful and should be used. However, they are not always used today, mainly because of the difficulty of computing accurate failure or launch delay probabilities, and because of the difficulty in establishing utility functions for an optimization.

5.0 COMPUTING STATISTICS OF WIND PROFILE EFFECTS

The dominant wind effects are a result of wind profiles, therefore, it is important to compute the statistics of these effects with some accuracy. The three main techniques for doing this make use of the large amount of existing wind profile data.

5.1 Synthetic Wind Profile Technique

In general, a synthetic profile is in a single plane and is designed so that the wind velocity increases with altitude to a peak velocity in the region of the tropopause. Often the shear used in building to the peak velocity, and the peak velocity itself, are of a magnitude with the same probability of exceedance. In other words, the assumption is made that unity correlation exists between velocity and shear in the tropopause region. The synthetic profile shown in Figure 3 can be considered typical, although most contain at least one more shear of shorter length but greater magnitude before the peak velocity is reached. Many variations of the basic synthetic profile shape are being used by various contractors and agencies, mainly as design criteria. Interesting discussions of the relative effects of some of these profiles can be found in (4) and (8).

Wind profiles are being used to some extent to obtain statistical data regarding wind profile effects. For example, a profile containing shears and velocities with a 1 percent probability of exceedance may be assumed to produce a 1 percent structural moment in the simulation of a missile flight. However, the inaccuracies resulting from such an assumption can be large, depending upon the missile characteristics, upon the effect of interest, and upon the direction of the wind relative to the missile trajectory (9).

5.2 Statistical Techniques

There are several techniques, (1) and (2), which have been developed that essentially compute a set of influence coefficients or weighting factors. These coefficients give the relationships between the wind profile and the wind profile effects and are computed from wind profile statistics. The required statistics are (1) the average of N-S and E-W wind components, (2) the standard deviations of N-S and E-W wind components, and (3) the correlations between the wind velocities and between the wind directions for a number of altitudes. Such statistics are presently available, but they have questionable accuracy and are available for a limited number of geographical locations.

The advantage of the above techniques is that once the coefficients are computed, the wind effects statistics can be computed without simulating the missile through a set of random or synthetic profiles. The disadvantages are: (1) the loss of accuracy due to the assumptions that the wind components are normally distributed and that the equations of motion are linear, which allows superposition to be applied; (2) the difficulties involved in checking the answers for reasonableness due to the artificiality of the techniques; and (3) the conceptual difficulties encountered by one not trained in statistics.

5.3 Profile Sample Technique

This technique computes the statistics of the wind effects by simulating the missile flight through an independent random sample of actual profiles. It was first used by Avidyne Research, Inc. (4).

The advantage of this technique is that sufficient information can be obtained from a random sample regarding all wind effects to completely describe their statistics at every altitude with any desired confidence and accuracy. Also, this technique is very closely tied to reality so that answers can be checked and a "feel" for the effects of winds can be obtained.

The chief disadvantages are:

(1) The confidence limits for any given accuracy are a function of the number of profiles used, and the cost of the simulations can become critical when high confidence is required.

(2) A change in missile design or trajectory can change the statistics of the wind effects for the new design and can thus necessitate the repetition of a large number of simulations.

The design method presented in this report will utilize the profile sample technique. Therefore, its use and possible techniques for overcoming the above disadvantages are discussed in detail in the following section.

6.0 USE OF THE PROFILE SAMPLE TECHNIQUE

The proposed methodology uses a set of independent random profiles for computing the effects due to wind profiles. The use of these profiles involves (1) selecting the profile sample, (2) simulating the missile flight through the profiles, (3) reducing the data to a useful form, and (4) checking the effect of any missile design and trajectory changes. These steps will now be discussed individually.

Step 1: Selection of Profile Sample

Wind soundings by means of balloons have been performed at regular intervals (typically, four times a day) at a large number of locations for many years. Avidyne Research, Inc., has obtained from this mass of data an independent random sample of 200 profiles for the winter months at seven locations that are

more or less evenly distributed throughout the United States (5) and (9). Samples are also being prepared for a number of locations outside the continental United States.

The sample selected for any given missile design would be from the location that would be most representative of the launch site. If the missile was to be launched from several sites, only the most severe of the representative samples is usually considered. However, if it is not clear which sample will produce the severest effects, it may be necessary to use several samples.

The size of the sample is dependent upon the accuracy and confidence limits that are desired. A sample size of 200 was chosen by Avidyne to provide a reasonable compromise between the amount of computation required, and the accuracy and confidence level obtained. A relationship which is used in determining the sample size is:

$$n = \left(\frac{\beta}{acc}\right)^2 \left(1 + \frac{a^2}{2}\right)\left(\frac{\mu}{\sigma} + a\right)^2$$

where:

- n = Size of sample taken from the normal distribution, $f(x)$, with mean, μ and standard deviation, σ.
- β = Number of standard deviations required such that the cumulative normal distribution evaluated at β equal $(C+1)/2$.
- C = Confidence = Probability that the desired probability of exceedance will fall within the specified accuracy when sample of size n is taken from $f(x)$.
- acc = Specified accuracy = Maximum allowable error of $\mu + a\sigma$
- a = Number of standard deviations needed to reach desired probability of exceedance.

The above equation assumes that the population distribution is normal and that the ratio of μ/σ is known. As an approximation, the ratio of sample mean to sample standard deviation is used instead of μ/σ for the evaluation of n when μ/σ is not known. If the distribution of the population is not known, the sample size for a given accuracy and confidence level increases greatly.

For an accuracy of 5%, a ratio of μ / σ of 1.7, an α of 2.33 (1% probability of exceedance), and a β of 1.65 (90% confidence), the equation given above gives a sample size, n, of 200. If the form of the probability distribution is unknown, a sample size of around 2500 is needed under the same conditions (10).

Step 2: Simulations

Since the number of simulations can usually be cut only at the sacrifice of confidence limits, the cost of simulations can best be reduced by optimizing the simulation techniques. This optimization could include a trade-off between computer time and simulation accuracy. However, care must be taken since a simplification may have effects on accuracy that vary widely with missile characteristics. Digital simulations are most common, although an analog simulation could prove less expensive if proper function generators could be used, and particularly if several simulations with small differences in missile characteristics were desired for each profile.

Step 3: Data Reduction

Enough data is computed by these simulations to establish probability distributions for the magnitude of all wind effects at every altitude or altitude increment, and in both pitch and yaw. However, the probabilities of interest to a missile designer are the probability of failure or launch delay due to winds aloft - both for any given missile design. How the data from the simulations can be used to compute the probabilities will be discussed later in this report.

Step 4: Recomputing Statistics for Change in Missile Configuration

Changes will often be made to the missile configuration or trajectory during the design process that will appreciably change the wind effect statistics. If these changes occur after the original simulations through the profile sample were completed, the designer is faced with the alternatives of repeating the full number of simulations or of attempting to extrapolate to a new set of statistics by a less costly and probably less accurate technique.

Several possible techniques for avoiding a repetition of simulating through the complete original sample are discussed below. Extreme caution should be exercised in applying any of these techniques to a new situation.

(1) Profile Selection By Assumptions 5 and 9

The assumption is made that the profiles that gave the largest wind effects for the original vehicle configuration will still give the largest effects for the new configuration.

The new configuration is then simulated through perhaps 25% of the original sample to produce the upper part of the cumulative probability curve.

(2) Profile Selection by Simplified Simulation (3).

Here the selection of the worst profiles for the new configuration is accomplished by using quasisteady equations to quickly estimate the wind effect magnitudes from each of the profiles in the original sample. Then, by complete simulation through these worst profiles the interesting upper part of the cumulative probability curve can be constructed.

(3) Sector-Profile Method (6)

The assumption is made that a given profile in a given compass sector will produce a wind effect magnitude with a probability of exceedance which does not vary for any member of a class of missiles. In other words, the magnitude of the wind effect produced by the profile may change, when the configuration or trajectory of a nominal missile is perturbated, but the statistical meaning of the effect produced will remain the same. This technique was developed for the unsymmetrical missile configuration and includes the solution for a symmetrical missile as a special case.

7.0 DISCUSSION OF PROPOSED DESIGN METHODOLOGY

The terms used in discussions of the methodology were defined in 3.0. However, a discussion of these terms is provided in the following paragraph to further clarify their meanings.

A missile encounters effects due to a number of factors such as wind profiles, profile detail, and buffeting; all of these factors except wind profiles are classified as non-wind profile factors. All factors cause effects (structural loads, control system perturbations, etc.), but when these effects are caused by a wind profile they are termed wind profile effects. Parameters which characterize the effects due to both wind profile and non-wind profile factors are termed effect parameters (bending moment, thrust vector angle). The reason for separate classifications of wind profile effects and non-wind profile effects is that they are handled differently in the methodology. Wind profile effects are computed from simulations through a random set of wind profiles. The statistics of these effects are never explicitly described. Non-wind profile effects are computed by considering the amplitudes of each effect parameter resulting from all non-wind profile factors in an interval of flight time. These effects are described by probability distributions of the maximum amplitude of each effect parameter in each time interval.

The heart of the design methodology being presented are the methods for the computation of probability of failure or launch delay for a given design. (These methods can also be used for studying the capabilities of an existing

missile). The methods are unique in that they consider random factors other than wind profiles and profile detail, they divide the flight into intervals of time, and they consider a probability distribution of only the maximum values of non-wind profile effects in a time interval.

The method for computing the probability of failure uses results of flight simulations through a set of random wind profiles and also probability distributions for non-wind profile effects in each interval. The probability of failure is computed first for each random profile in each interval of flight time (see Figure 5), then for each profile during an entire flight, and finally for all profiles in a random sample.

The method of computing the probability of launch delay first determines the launch allowable values for wind profile effects. This is done by subtracting an allowance for non-wind profile effects from the design allowable in each time interval (see Figure 6). The method then finds the probability that a random wind profile will cause a launch allowable to be exceeded.

Since the probabilities of interest can only be found for a given design, the process of designing to the criteria of 4.0 is necessarily iterative. The design may have to be changed several times before one with the desired probability value, or with an optimized probability, can be found. This is a difficult process requiring use of large computer installations and a good deal of engineering judgment. However, it is often worthwhile because of the importance of obtaining a good design.

The advantages of the proposed methodology are (1) that computational steps are closely tied to reality, and (2) that the amount of computation can be varied according to the degree of accuracy desired in the design. The disadvantage is that two major simplifying assumptions regarding non-wind profile effects have to be made to keep the necessary computations from becoming more complex and costly than is justified for the amount of basic data now available.

The two main assumptions used in the methodology are stated and discussed below. Assumption 1 can be modified under special conditions to be less inclusive. A clarification of this statement will be included in the discussion of Assumption 1.

Assumption 1: Unity Correlation Exists Between All the Probability Distributions of all the Effect Parameter Magnitudes Resulting from Non-Wind Profile Factors.

The assumption means that, when non-wind profile effects are considered, there is unity correlation between two different effect parameters in the same time interval, between two different effect parameters in the different time intervals, and between the same effect parameter in two different time intervals.

This assumption is necessary because the methodology usually divides the period of flight in which the probability of failure due to winds is appreciable into a number of time intervals (see 8.0), and because the

methodology considers the possible failure of the missile to be due to any effect parameter exceeding its design allowable. In the methodology, the wind profile effects versus flight time are computed for each profile from the random wind sample being used; and, since the probability of failure is first computed for each profile, the wind profile effects are used as deterministic values. However the effect parameters for non-wind profile effects are probable, and correlations between them in one time interval or two different time intervals must be used in the methodology. It is known that these correlations are high, but in the present state-of-the-art they cannot be computed. (Since the dominant non-wind profile effects are usually due to profile detail, additional statistical data regarding profile detail is particularly needed).

The assumption of unity correlation simplifies computations because it means that the probability of failure for one profile is due to the highest probability of any effect parameter in any time interval exceeding its design allowable. Without such an assumption, multivariate distributions must be utilized; and published tables describing such distributions are available only for the cases of two or three variables. Thus, only in the special case of an unusually small number of time intervals and/or critical effect parameters, could this methodology be used in the practical case without the assumption of unity correlation.* Although approximations could be made in any problem to decrease the number of variables, the inaccuracies could be as damaging as the unity correlation assumption itself. Therefore, the methodology described is only for the condition that Assumption 1 is being used.

The most undesirable feature of the assumption is that it is unconservative -- it reduces the computed probability of failure. Therefore, the effect of the assumption must be examined carefully for any specific probability computation. The errors which will result from the assumption are proportional to the number of time intervals used and to the number of effect parameters that have an appreciable probability of exceeding their design allowable. Also, the absolute errors decrease as the magnitude of the non-wind profile effects decrease, for it must be remembered that this assumption does not apply to the consideration of the usually dominant wind profile effect magnitudes. Finally, although a number of time intervals are considered, often the probability of failure in one time interval is much larger than in the other time intervals for most of the profile simulations. Such a situation also decreases the errors due to the assumption.

Assumption 2: The Magnitudes of an Effect Parameter Caused by all Non-Wind Profile Factors can be combined Algebraically with Each Other and with the Magnitude of the Same Parameter Caused by a Wind Profile.

This assumption means that if a wind profile produced an effect parameter such as a bending moment in one plane of a missile (e.g. pitch plane), then the bending moment due to all non-wind profile factors (such as profile detail, buffeting, etc.) also occurs in that same plane. Thus, the effects can be combined by simple addition or subtraction.

* An exception results from a new technique described in, "Evaluation of the Normal Distribution with Many Variables For the Case of Low Probability of Failure" M. Schwartz, Aerospace 1951 2-217, August 1962.

This is a common assumption in wind studies. It can be justified on the basis that (1) it is conservative, (2) the data for more exact computations is not available, (3) the consideration of random directions would probably be prohibitively difficult, and (4) the most important non-wind profile factor, profile detail, is believed to exist mainly in the plane of the wind profile. In practice, what a designer must do is to estimate equivalent non-wind profile effect magnitudes in the compass sectors containing the dangerously high wind profile velocities.

8.0 COMPUTING THE STATISTICS OF NON-WIND PROFILE EFFECTS

The methodology of this report requires the determination of the probability distribution of the maximum magnitude of each critical effect parameter resulting from all non-wind profile factors for each interval of flight time in which winds are an important factor. (Such a distribution is shown in Figure 5.) To do this, one must first choose the time intervals. Then, for each interval, one must compute the probability distribution of each effect parameter for each factor. Finally, a combined distribution of each effect parameter for all factors is determined in each interval. A detailed discussion of these three steps follows.

Step 1: Selection of Time Intervals

The period of flight of interest is only that in which there is an appreciable probability of failure due to winds. It is assumed that the probability of failure at any other time-of-flight is zero. The period is then divided into time intervals such that the probability of failure during each interval is approximately constant with time.* The shorter the interval the more constant is the probability, but it is desirable to use long intervals in order to simplify computations and reduce inaccuracies due to Assumption 1 in 7.0. The choice of the intervals is therefore often a compromise, and it is always an estimate. One must consider variations with time of the design allowables, the non-wind profile effects, and the wind profile effects. An example of a large change in non-wind profile effects with time would be the advent of buffeting in the region of Mach 1. Wind profile effects will also change around Mach 1 due to changes in aerodynamic coefficients. Typically, the period of flight from 25K to 40K feet altitude is divided into time intervals of 10 seconds or more.

Step 2: Computation of Statistics for Each Effect Parameter Magnitude Resulting from Each Non-Wind Profile Factor

For each effect parameter of interest (e.g., bending moment), a probability distribution of its maximum amplitude must be found for each non-wind profile factor (e.g., profile detail) in each time interval. These distributions will be approximated as normal probability distributions, and the necessary data for the approximations are obtained from past flight tests, simulations, etc. Normal distributions are approximated in order to simplify the combination of distributions that will be discussed in Step 3.

* Each interval is therefore representative of one phase of flight.

Since some correlation exists between profile detail (the dominant non-wind profile factor) and wind velocity, a different probability distribution should be used for each level of wind profile velocity. In other words, conditional probability distributions could be approximated for each condition of wind profile - or even for each condition of wind profile effects. The data for such conditional probabilities does not now exist. An alternative to the use of a number of conditional distributions is to use a conditional distribution for a high wind profile velocity or profile effect, since only under such conditions is there usually an appreciable probability of failure. This alternative will cause a conservatively large probability of failure to be computed.

The computations for one effect parameter (structural bending moment) due to one non-wind profile factor (profile detail) in one time interval are discussed in the following paragraph to clarify the procedures necessary for this step.

Assume that wind velocity and wavelength statistics for profile detail are available for all altitudes of interest. (These statistics should be for the a priori condition of a high wind profile velocity.) A fixed time simulation (the velocity vector, altitude and missile parameters are fixed) is then performed at a representative time-of-flight in the time interval with the missile being excited by the power spectrum of the aerodynamic forces due to profile detail. This simulation is continued for time equal to a large multiple of the time interval, and the bending moment at the critical missile station (the location with the highest probability of having its design allowable exceeded) is recorded. This recording can then be divided into increments equal to the time interval under consideration, and the maximum positive (negative) bending moment during each increment is measured. It is important to consider only all positive or all negative moments, for in flight only one will add to the wind profile effect. Consideration of a maximum absolute magnitude could produce distorted results. Either positive or negative can normally be used since the effects are usually symmetrical. An illustration of results from such a simulation is shown in Figure 4. Note that the period of the dominant frequency of the bending moment (usually a result of the first flexible body mode) is considerably shorter than the time interval. This makes the concept of maximum magnitude in the interval more meaningful.

A normal probability density can be approximated for the measured maximum bending moment. This distribution will have a non-zero mean, as is shown in Figure 4.

<u>Step 3</u>: Computation of a Combined Distribution in Each Interval for Each Effect Parameter Magnitude Resulting from All Non-Wind Profile Factors.

A probability distribution from Step 2 of the maximum amplitude of one effect parameter for one non-wind profile factor in a time

interval must be combined with the distributions of the same parameter caused by all other non-wind profile factors in that interval. Since all are approximated as normal distributions, and since all are assumed to act in the same direction (Assumption 2 in 7.0), this can be accomplished by the well known formulas given below. This must be done for each effect parameter in each time interval.

$$\text{Combined Mean} = \sum_{j=1}^{N} \mu_j$$

$$\text{Combined Variance} = \sum_{j=1}^{N} \sigma_j^2 + 2r_{jk} \sum_{j=1}^{N} \sum_{k=1}^{N} \sigma_j \sigma_k$$

where: μ_j = mean of j^{th} probability distribution

σ_j^2 = variance of j^{th} probability distribution

r_{jk} = correlation coefficient.

$j \neq k$

N = No. of combined variables.

The factors listed in Section 3.2 are essentially independent, so that the correlation coefficient, r_{jk}, is normally zero; however, the methodology does not require independence.

9.0 DESIGNING FOR PROBABILITY OF FAILURE

As previously defined, the probability of failure is the probability that the design allowable of any effect parameter (bending moment) will be exceeded at some time during flight. The methodology for designing to a given probability of failure, or to an optimum probability of failure, is outlined in the steps listed below. If it is desired to check an existing missile, the last step can be deleted. In the methodology, the probability of failure will be computed first for each random profile in each time interval for all effect parameters, then for each profile during an entire flight, and finally for all profiles in the random sample.

Step 1: Computation of Design Allowables

A specified design allowable curve (defined in Section 3.3) versus time (during the period in which winds can endanger the flight) is needed for each effect parameter that may have an appreciable probability of exceeding its allowable. (Several allowable curves will be needed for each effect parameter for an unsymmetrical vehicle as is shown in Appendix I.) Parameters that could be critical are discussed in Section 3.0. Usually only one or two effect

parameters need be considered for any one vehicle. The computation of design allowables is a normal part of a missile design and will not be discussed here.

Step 2: Selection of The Sample of Random Wind Profiles

An independent random sample of profiles which are obtained from balloon soundings must be chosen. The location of the balloom launching site and the size of the sample must be carefully considered as described in Section 6.0.

Step 3: Simulations Through Sample Profiles

The flight of a nominal missile of a given design must be simulated through each of the profiles. The time history of each effect parameter of interest from each simulation can be plotted on graphs showing the design allowable curves. Such a graph is shown for a symmetrical structural load in Figure 5. See Appendix I and Figure 7 for consideration of an unsymmetrical design allowable curve.

Step 4: Selection of Time Intervals

Any period of flight in which the effects of winds are critical may have to be divided into time intervals. The choice of time intervals was discussed in Section 8.0.

Step 5: Computation of Probability Distributions for Non-Wind Profile Effects

The combined probability distributions for the maximum amplitude of each effect parameter of interest resulting from all factors except wind profiles must be computed for each time interval. Such computations were discussed in Section 8.0.

Step 6: Determination of Average Difference Between Wind Profile Effect Magnitudes and Design Allowables in Each Time Interval for Each Profile

If the magnitude of an effect parameter resulting from only the wind profile exceeds a design allowable value in any time interval, it is clear that the probability of failure for that profile is unity. However, even if a win' profile alone does not cause failure, there is always some probability that the additive non-wind profile effects can cause failure. To compute that probability for each profile, the difference between the wind profile effect magnitude and the design allowable must be computed in each time interval for each effect parameter of interest. Since both may be changing during the interval, some discretion must be exercised in this computation. The difference between the averages is usually the best approximation, as is used in Figure 5.

Step 7: Computation of the Probability of Failure in Each Time Interval for Each Profile

The probability of failure for each profile in each time interval is determined by first finding the probability that the magnitude of each effect parameter resulting from non-wind profile factors will exceed its difference value found in Step 6. These probabilities can be obtained graphically by integrating the area under the part of the effect parameter probability distribution curve that exceeds the difference (as shown in Figure 5). They can also be obtained from tables of the cumulative normal distribution. This step utilizes Assumption 2 in 7.0. Using Assumption 1 in 7.0, the probability of failure in each time interval for each profile is simply the highest probability of any effect parameter exceeding its differential value due to all non-wind profile factors.

Step 8: Computation of the Probability of Failure for Each Profile

If Assumption 1 in 7.0 is used, then the probability of failure for each profile for any effect parameter during an entire flight is simply the highest probability of failure in any time interval for any effect parameter. (If Assumption 1 is not used so that correlations are arbitrary, then multivariate distributions must be utilized as described in the discussion under Assumption 1 in 7.0.)

Step 9: Computation of the Probability of Failure for the Profile Sample

The probability of failure associated with each profile in the selected random sample was found in Step 8. The probability of failure for the entire sample is the sum of the probabilities for the individual profiles divided by the number of profiles in the sample. This is the actual probability of failure for the given design within the accuracy and confidence limits determined by the size of the sample.

Step 10: Iteration of the Design to Meet the Design Criteria

If one is designing to a given probability of failure, and if Step 9 shows that the original design does not meet the criteria, then the design must be changed. If the change is of a type that causes the wind effects to change, then they must be recomputed as discussed in Step 4 of Section 6.0. In any case, the new design allowables must be found, and a new probability of failure computed. Still further iterations could be necessary, although rapid convergence to a reasonable accuracy of design would be expected.

If one is designing to an optimum probability of failure, some utility function (criterion used in the optimization of a system) must be established to allow a trade-off between probability of failure and some other parameters (such as weight, cost in dollars, schedule slippage, etc.). An iterative design procedure would then be followed.

10.0 COMPUTING LAUNCH ALLOWABLES

Many large boosters carrying space vehicles are not designed to withstand extreme wind conditions which have an appreciable probability of occurrence. Since it is usually preferable to delay the flight under such conditions rather than risk a failure, prelaunch wind checks are performed. Based on these checks (normally in the form of balloon soundings), predictions are made of the magnitude of wind profile effects that will be encountered in flight. If the predicted values exceed a launch allowable (defined in 3.5), then the launch is delayed until the predicted values decrease. Such a procedure is described in Appendix II. The launch allowables are so selected that, when a flight is permitted on the basis of the allowables, the probability of failure due to winds in that flight is less than some assigned value (usually a negligible value).

Launch allowable values are assigned only to wind profile effects, since only they can be predicted with any reasonable accuracy. Thus, statistics of non-wind profile effects must be precomputed, and an allowance for these effects must be subtracted from the design allowables in each time interval. The computation of these non-wind profile effects is discussed in 8.0. However, in order to arrive at the launch allowables, a further allowance must be made for uncertainties in the accuracy of the predicted wind profile effects. These uncertainties are a result of (1) possible inaccuracies in the prediction process, and (2) possible variations in the wind characteristics between the time of the last balloon sounding and the actual launch time.

Inaccuracies in the prediction process are dependent on the techniques used. If the simulations are made through wind profiles measured before launch, errors can occur due to inaccurate data or approximations in the simulation. If only precomputed regression curves (one such curve is shown in Figure 11) are used for prediction, even larger errors could be encountered. Variations in wind characteristics between balloon soundings and launch are dependent on prior wind conditions and upon the length of time involved. Naturally, every effort is made to keep the time between sounding and launch to a minimum in order to minimize these variations. Normal probability distributions are approximated for the effects of these new uncertainties as was done with the non-wind profile effects, and independence is assumed. Thus their distributions can be easily combined with those of the non-wind profile effects.

The allowances for prediction uncertainties to be subtracted from the design allowables, are found from such a combined probability distribution and reflect all of the flight uncertainties except the wind profile. This probability distribution is computed for each effect parameter in each time interval. A magnitude for each effect parameter in each interval is then chosen with a probability of exceedance equal to the probability of failure that is allowed when the decision to launch is made. These allowances are then subtracted from the design allowables to obtain the launch allowables. An illustration of this procedure is shown in Figure 6.

If it is assumed that unity correlation exists between all the combined probability distributions of uncertainties (similar to Assumption 1 of 7), then the probability of failure for an allowed flight cannot be more than the probability of failure in any one time interval.

11.0 DESIGNING FOR PROBABILITY OF LAUNCH DELAY

The computation of launch allowables is discussed in 10.0. Since a launch will be delayed whenever a wind profile effect predicted by some procedure before the launch exceeds a launch allowable, it is necessary to compute the probability of such an event for a given missile design in order to perform a design for some probability of launch delay. (one procedure for predicting wind profile effects is given in Appendix II.) The computation of a probability of launch delay for a given design as performed in the proposed methodology usually makes use of the assumption discussed below. The discussion includes a short description of a methodology to be used if the assumption is not utilized.

Assumption: The Wind Profile Effect Statistics Obtained by Simulations Through a Set of Random Wind Profiles Will Be Representative of a Random Set of Predicted Wind Profile Effects.

The assumption means that the same statistical parameters for the magnitude of an effect parameter, such as bending moment, would be obtained from a random sample of prelaunch predictions of bending moment as from simulations through a random sample of profiles.

This assumption is valid when there is no error in the wind effect predictions, but this will never be completely true. No bias will usually exist in the predictions, so the mean value of a predicted effect parameter is the same as the mean obtained from simulations using random profiles. However, there will be errors in the predicted values that can cause the standard deviation of a predicted effect parameter to be greater than the standard deviation obtained by using the random profiles. This larger standard deviation means that the predicted wind effects will exceed a launch allowable a larger percentage of the time, and the probability of launch delay will increase. Therefore, the probability computed on the basis of this assumption is unconservative.

Not only is the assumption unconservative, but it is inconsistent with the allowance for a prediction error that was used when computing the launch allowable curve in 10.0. However, the allowance for prediction errors should remain even if this assumption is used, for minimizing flight failure is certainly more important than an inaccuracy in a computed launch delay probability.

The assumption is used for many of the reasons stated for previous assumptions, namely: it simplifies the computations,

data for an accurate computation is not available, and, the error encountered in its use should not be appreciable in mose cases.

The magnitude of error that results from the assumption decreases as the accuracy of the prediction process increases. If it is planned to use a complex procedure such as described in Appendix II, then the assumption should be reasonable. However, the planned use of a relatively crude procedure could make it necessary to consider the prediction error. A method of doing this is described in the following paragraph.

If the above assumption cannot be used, then the probability of launch delay can be computed in the same manner as was the probability of failure in 9.0. In this case, however, an estimate of the probability distribution for each effect parameter due to prediction errors must be added to the result of each profile simulation in each time interval. The probability of exceeding the launch allowable can then be computed in each interval for each profile, then for each profile, and finally for the entire profile sample. These computations can be simplified by the use of an assumption similar to Assumption I in 7.0 - that is, unity correlation can be assumed between all distributions of the effect parameter magnitudes resulting from prediction errors.

The methodology for designing to a probability of launch delay or optimizing the probability is outlined in the following steps using the foregoing assumption.

Step 1: Selection of Time Intervals.

This is done as described in Section 8.

Step 2: Computation of Launch Allowables.

See Section 10.

Step 3: Selection of Sample of Random Wind Profiles.

See Section 6.

Step 4: Simulations Through Sample Profiles.

The flight of a nominal missile of a given design through each of the profiles must be simulated.

Step 5: Comparison of the Results of the Simulations with the Launch Allowable Curves.

The time history of each effect parameter of interest from each simulation can be effectively plotted on a graph showing its launch

allowable curve. This is illustrated for a symmetrical vehicle in Figure 6. See Appendix I and Figure 8 for consideration of an unsymmetrical vehicle. The graphs will show when an effect parameter exceeds its launch allowable curve.

Step 6: Computation of the Probability of Launch Delay.

The fraction of the random profiles that cause a launch allowable for any effect parameter to be exceeded is the probability of launch delay with an accuracy and confidence proportional to the size of the sample of profiles.

This computation is meaningful when the following statements are true:

(1) A launch delay decision is always based solely on the criteria that a predicted effect exceeds its launch allowable.

(2) The decision to delay a launch is always made at one scheduled time in the countdown.

This statement must be assumed to be true in order to avoid consideration of the increased probability of launch delay that would be encountered when wind profile effect predictions and launch decisions are made several days before launch. (See Appendix II.) It is normally true because, in an actual situation, the launch delay decision is usually postponed to just before launch in the hope that winds may improve, and because persistence of winds makes the probability of delay relatively insensitive to decision time over a period of several hours.

Step 7: Iteration of the Design to Meet the Design Criteria.

If one is designing to a given probability of launch delay, and if Step 6 shows that the original design does not meet that criteria, then the design must be changed. If the change is of a type that causes the wind effects to change, then they must be recomputed, as discussed in Section 6. In any case, the new launch allowables must be found and a new probability of launch computed. Still further iterations could be necessary, although rapid convergence is expected.

If one is designing to an optimum probability of launch delay, some utility functions must be established to allow a trade-off between probability of delay and some other parameter (such as weight, cost in dollars, schedule slippage, etc.). An iterative design procedure would then be followed.

12.0 CONCLUDING REMARKS

The presentation of this methodology has attempted to consider the general case - that is, consideration of all possible vehicle configurations and a range of requirements on the desired accuracy of the results. This

makes the procedures appear more complex and burdensome than they need be for a specific situation. Actually, the mechanics of performing some of the steps can be simplified by tailoring them to one's needs and computing facilities.

Studies are being conducted at Aerospace in an effort to develop a design methodology that utilizes the concepts presented here, but uses reduced statistical data from the simulations through the random profiles instead of dealing with one profile at a time. Apparent advantages are increased mechanization of computation and greater flexibility in the assumption of correlation coefficients. The main disadvantage appears to be a loss of physical reality. Such a loss makes it more difficult to check answers for reasonableness and to apply engineering judgment.

It is of interest to examine the type of additional meteorological data that would improve the accuracy of the type of methodology presented here. The most valuable data would describe profile detail, and should include the statistics of wavelength and magnitude as well as the correlations between altitudes with wind profile characteristics.

In connection with the gathering of data on profile details, there is some question as to how wind data should be divided to separately describe wind profiles and profile detail. There are arguments for continuing to have the statistics for profile detail include all wind characteristics that have shorter wavelengths (wavelength is in feet of altitude) than the wavelengths detected by present balloon sounding techniques. The alternative is to use balloon sounding techniques that detect wind changes over smaller altitude layers, and to include this data in the statistics that describe the wind profiles. The separately defined statistics for profile detail will then include wind characteristics with a narrower wavelength spectrum. The arguments for maintaining the present wavelength division of wind statistics are: (1) a great mass of balloon sounding data already exists, and (2) there are differences in the effects and persistence characteristics of the smoothed profile and the profile detail. The effects differences are largely due to the fact that almost all the dynamic effects come from the profile detail, as contrasted with the quasi-steady state effects of a smoothed profile. This usually demands a division of analysis techniques. The difference in persistence characteristics (these differences are yet to be determined) would be of importance when attempting to predict wind effects to be encountered in a flight. Here again, a division of techniques, one for the smoothed profile and one for detail, may have to be used for the prediction process.

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APPENDIX I

CONSIDERATION OF AN UNSYMMETRICAL VEHICLE

The design allowable bending moment curves (defined in Section 3.3) shown in Figure 5 and 6 of this report were for a symmetrical vehicle - that is, the allowable bending moment at the applicable missile station is the same in all directions about the longitudinal axis. Most missiles do tend to be symmetrical in regards to allowable bending moment. However, there is usually enough aerodynamic dissymmetry so that the allowable dynamic pressure, q, times the angle between the body axis and the relative wind velocity, $(\alpha^2 + \beta^2)^{1/2}$, varies with direction (see Figure 7). The importance

of this arises from the fact that the structural load computed in a simulation through a wind profile, whether in a random wind study or as part of a prelaunch wind check, is usually in terms of $q\sqrt{\alpha^2 + \beta^2}$ because it requires additional computation to obtain bending moment at the critical station. Thus design allowable curves and launch allowable curves are often used in terms of $q\sqrt{\alpha^2 + \beta^2}$ and, when they are unsymmetrical, special graphical techniques are required for the methodologies presented in the main body of the report. Handling of the dissymmetry in computing the probability of failure and in performing a prelaunch wind check are discussed here.

The computation of the probability of failure associated with one random profile in one time interval, for an unsymmetric design allowable curve is illustrated in Figure 7. Note that the non-wind profile effects are assumed to add in the direction of the wind profile effect (Assumption No. 2, Section 7). A representative design allowable curve as shown in Figure 7 must be used for each time interval to permit the computation of a total probability of failure.

An assymmetrical launch allowable curve (defined in Section 3.5) is often encountered when performing a prelaunch wind check and making a decision as to whether a launch should be allowed in the existing wind environment. (Such a procedure is described in Appendix II). This procedure often requires that a simulation be made of the vehicle flight through a wind sounding obtained by a balloon sounding made a few hours before scheduled launch time, and that a time history of $q\sqrt{\alpha^2 + \beta^2}$ be recorded from the simulation. The history of $q\sqrt{\alpha^2 + \beta^2}$ must then be compared with the precomputed launch allowable values in order to make a launch decision. If the vehicle is aerodynamically unsymmetrical, then the comparison can be made on a special chart of the type shown in Figure 8. That graph essentially breaks an allowable curve similar in shape to the one shown in Figure 7 into allowable $q\alpha$ and $q\beta$ components for a number of directions. It does that at a number of times of flight so that continuous allowable curves versus time can be drawn. With the simulation history plotted on the graph it is possible to see if it exceeds the allowables at any time; and, if not, to see at what time-of-flight it comes closest to the allowable curves. Interpretation of the graph is explained in Figure 8.

APPENDIX II

A PRELAUNCH WIND CHECK PROCEDURE

INTRODUCTION

In the case of most R and D launches, and particularly with a manned payload, it is preferable to check the winds before launch and to delay the launch if wind effects appear excessive. This report is concerned with performing optimum wind checks, where optimum is defined as delaying a minimum number of launches while allowing no failures due to wind.

The winds of concern here are winds aloft - as contrasted with ground winds, which involve separate procedures and criteria for the launch decision. The prelaunch check of winds aloft involves measuring the wind

velocity profile and predicting the wind effect magnitudes for the flight. Both of these operations, and improved prediction techniques, are discussed.

PRELAUNCH WIND MEASUREMENT

The wind measurement technique presently used at the Atlantic and Pacific Missile Ranges uses balloons that rise at roughly 1000 feet per minute and will go to about 100,000 feet. The balloon carries a transmitter which allows it to be tracked and atmospheric data measured by sensors attached to the balloon to be telemetered. The most common equipment used presently for balloon position measurement is designated as GMD-1. Some improved equipment coming into service is designated as GMD-2. With the GMD-1 equipment, the balloon position is determined by using the elevation angle to the balloon (measured by the tracking antenna) and the balloon altitude (computed from the telemetered atmospheric data). With the GMD-2 equipment the position is determined from the elevation angle and the range (both measured by the tracking equipment). The balloon position is determined at regular intervals, and the wind velocity is found from the rate of change of position. The computed velocity is thus the average velocity over an altitude layer, (normally 1000 feet or more), and that velocity is assigned to the altitude at the center of the layer. The results of such a balloon sounding has been termed a wind profile in this report. Since it is evident that this is a smoothed profile, the profile information that is not detected has been referred to as profile detail. In regards to the time required to take a sounding and compute the profile, it presently requires about 1 1/2 to 2 hours to get velocities to an altitude of 60K feet.

Improved balloon sounding techniques are presently being developed which will afford more accuracy and will provide average wind velocities over smaller altitude layers. A promising method uses a high pressure, constant rise-rate balloon and the FPS-16 tracking radar. Also, computer facilities can be improved for more rapid data reduction and perhaps some optimum smoothing.

Figure 9 shows a wind check schedule that is presently being used by the Aerospace Corporation. Note that wind predictions are used up to 12 hours before launch for making wind effect predictions, but actual sounding data is used after that time.

PREDICTION OF WIND EFFECTS

When any predicted wind effect magnitude exceeds its launch allowable the recommendation must be made to delay the launch. The prediction of the wind effect magnitudes is made on the basis of simulations through predicted and measured wind profiles and by means of the procedure that is outlined below.

Flight simulations are made using the T-2 day, T-1 day and T-12 hour predicted wind profiles, as soon as each profile is available. The wind effect magnitudes computed by the simulation are compared with the launch allowable values. In the case of an unsymmetrical vehicle the structural loading can be compared with the allowables by means of curves such as shown in

Figure 8. If a simulation shows that a predicted wind will cause the wind effect allowables to be exceeded, then an early decision to delay the flight could possibly be justified. However, such a decision would only be made after consultation with meteorological personnel, since the decision will certainly be influenced by the confidence assigned to such relatively long range predictions. In contrast, the decision regarding a delay in launch based on the complete procedure given here may be made less than an hour before launch time, so that the decision must be almost automatic. A short decision time is only workable if all parties concerned have reached prior agreement as to the criteria for decision.

During the last 6 hours or so before launch, a measured profile is usually the best prediction of the profile that will be seen in flight. Therefore, the T-5 1/2 hour and T-2 1/2 hour sounding data are used in making the final wind effect predictions.

When the data from the T-5 1/2 hour sounding is received, a simulation is made and the resulting wind effect magnitudes at the critical times-of-flight are plotted as "X's" at T-5 hours (the approximate time the balloon reached the altitude region of highest winds) on charts such as Figure 10. The critical time-of-flight for any wind effect considered here is the time at which its magnitude comes the closest to the allowable. In the case of structural loads, this critical time is found by plotting the computed loads versus time on a graph such as that of Figure 6 or Figure 8. (A graph is needed for each effect of interest.) Another set of wind effect magnitudes ("expected" maximum magnitudes) are obtained by taking the maximum wind from the sounding and then referring to regression curves of the type in Figure 11. These curves are usually obtained by simulating the missile through a number of random wind profiles, and they are meaningful because of the high correlation between wind velocity and wind effect magnitudes. These expected values are plotted as "0's", also at T-5 hours, and the differences ϵ_{T-5}, between the magnitudes from the simulation and the corresponding expected magnitudes are now computed.

No time is available to perform a simulation to compute wind effects using the T-2 1/2 hour sounding. However, the expected values are available from the regression curves. These values are then modified by ϵ_{T-5} to obtain more accurate values, and they are plotted as "X" at T-2 hours as illustrated in Figure 10. (The justification for the use of ϵ_{T-5} as a modifier is based on the assumption that the unique form of the profile that caused ϵ_{T-5} to have a value other than zero will tend to persist until flight time.) Final predicted values of wind effects can now be found by extrapolating to launch time the rate of change of magnitudes seen between the T-5 1/2 and T-2 1/2 hour sounding results. A final predicted value is shown in Figure 10 as "□", along with a simple geometric construction (dotted lines) to obtain it. This value can then be compared with the launch allowable value at the critical time-of-flight. If the predicted value exceeds the launch allowables, then the flight must be delayed.

Countdown holds which delay the launch often result from causes other than winds aloft. Such holds may necessitate a repetition of the previous wind sounding if (1) a total hold exceeding one hour occurs between the T-5 1/2

and T-2 1/2 hour soundings, or (2) a total hold exceeding T-45 minutes occurs subsequent to the T-2 1/2 hour sounding. Therefore, there must be a capability to perform at least two extra soundings.

IMPROVED WIND EFFECT PREDICTION TECHNIQUES

An optimum wind check procedure has been defined as one causing a minimum number of launch delays while still preventing any in-flight failures. Thus to optimize, the launch allowable values must be increased to a point where the probability of failure when a launch is permitted starts to become appreciable. Although admittedly "appreciable probability" is difficult to define; there is certainly a practical limit to the conservatism that can be used in computing the launch allowables. Less conservatism is possible, of course, when more accurate information is available regarding the uncertainties. Better information regarding profile detail and wind variability (particularly for conditions of high wind velocity) would be especially helpful. Improved wind soundings, in the sense of measuring finer profile detail, will also be helpful, for then a smaller statistical allowance need be made for profile detail.

Predicting wind effects by actually simulating the missile through prelaunch soundings has the great disadvantage of requiring the services of trained men and computing facilities for a long period before launch. A much better procedure would be to have the launch criteria merely a function of wind parameters (velocity, direction, shear), so that, once the wind sounding data was available, a simple table or chart could provide information for the launch decision. This would be practical (1) if the missile was so insensitive to winds that extreme conservatism could be used in forming criteria without creating a seriously high probability of launch delay, or (2) if enough studies of the vehicle of interest could be conducted to compute accurate correlations between wind effects and a number of wind parameters.

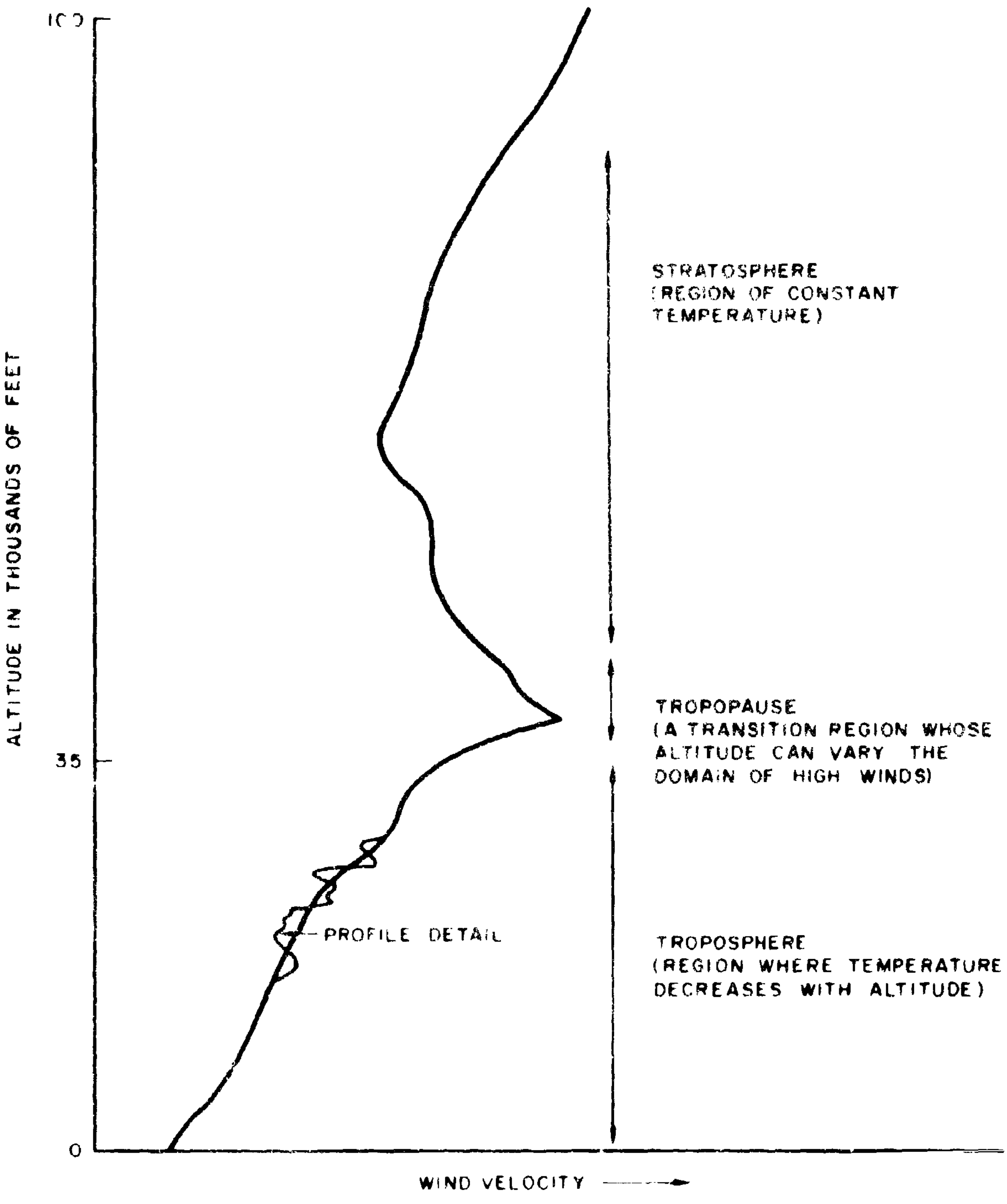
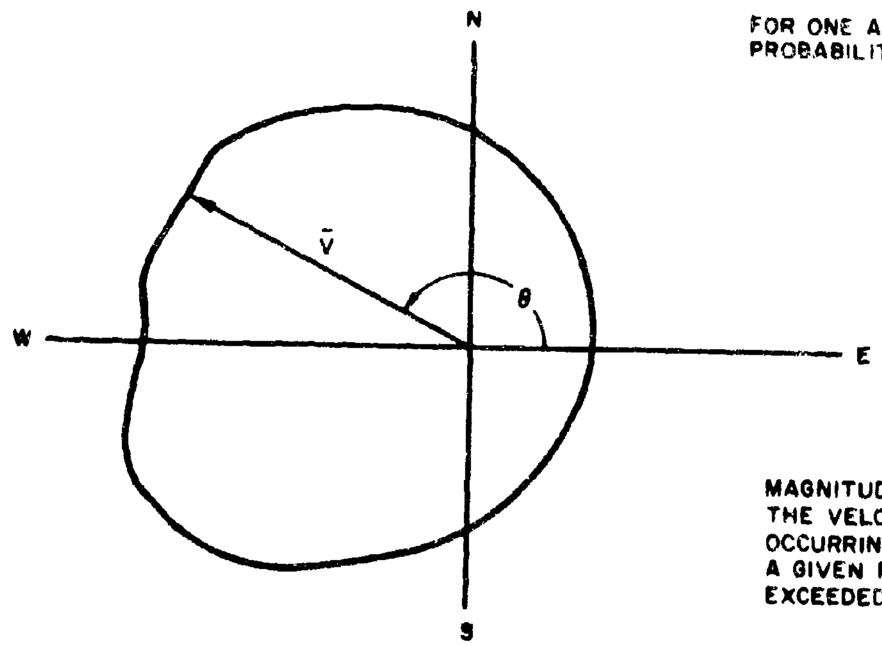


Figure 1. Typical Wind Velocity Profile



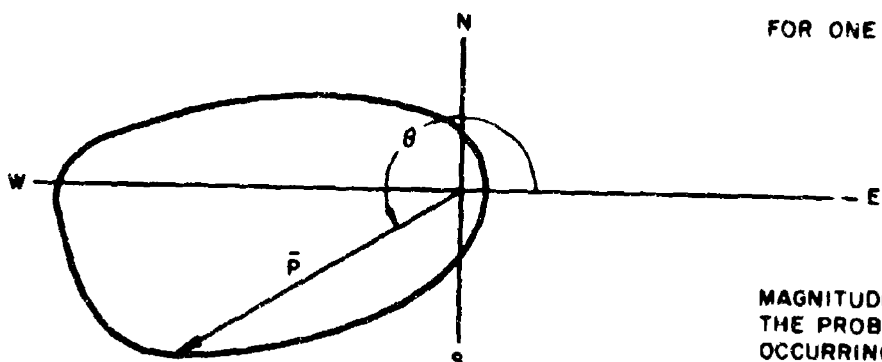
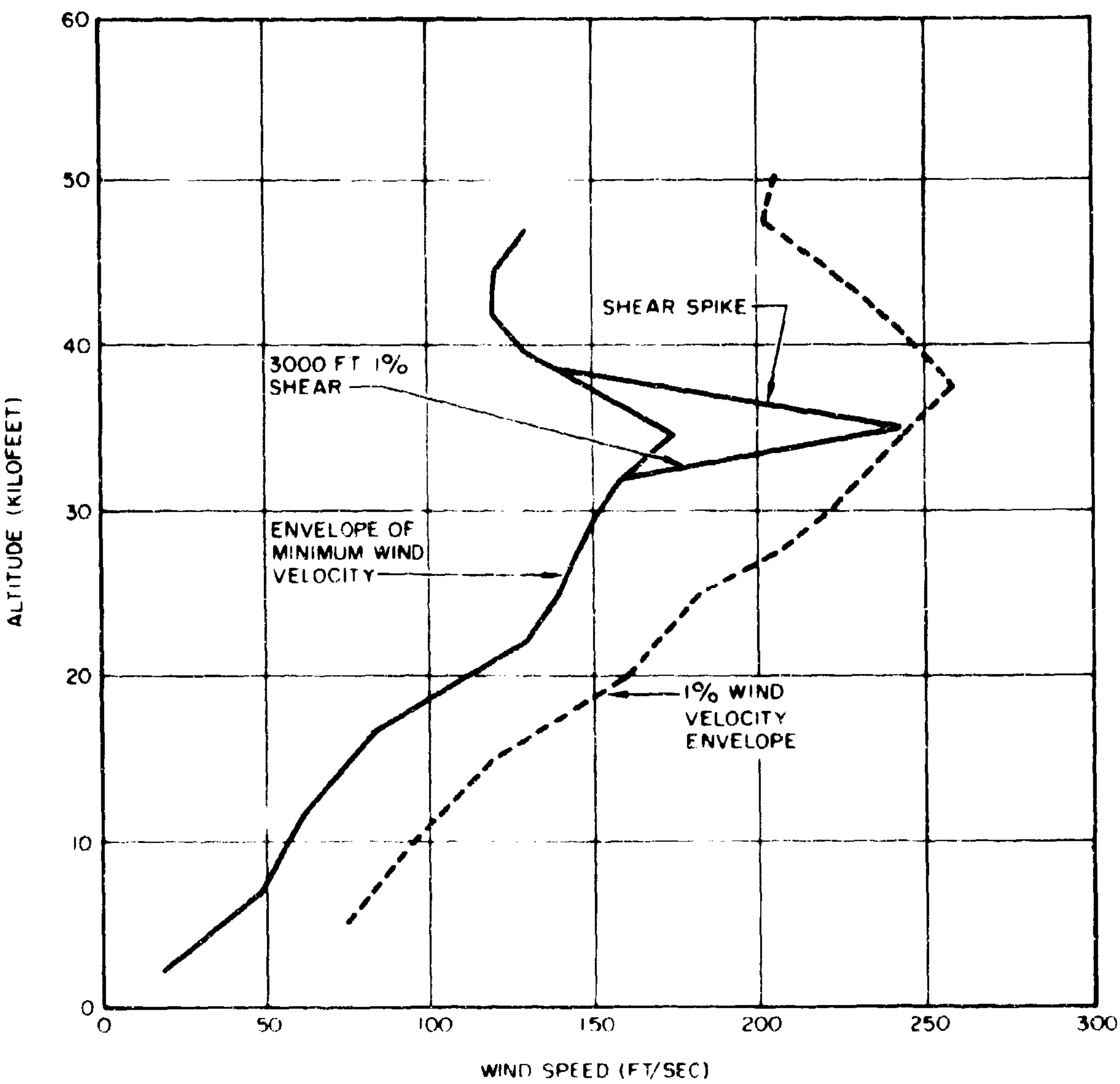


Figure 2. Typical Wind Roses



(A SHEAR SPIKE CAN BE INSERTED BETWEEN THE MAX AND MIN ENVELOPES AT VARIOUS ALTITUDES)

Figure 3 A Synthetic Wind Profile (Reference 5)

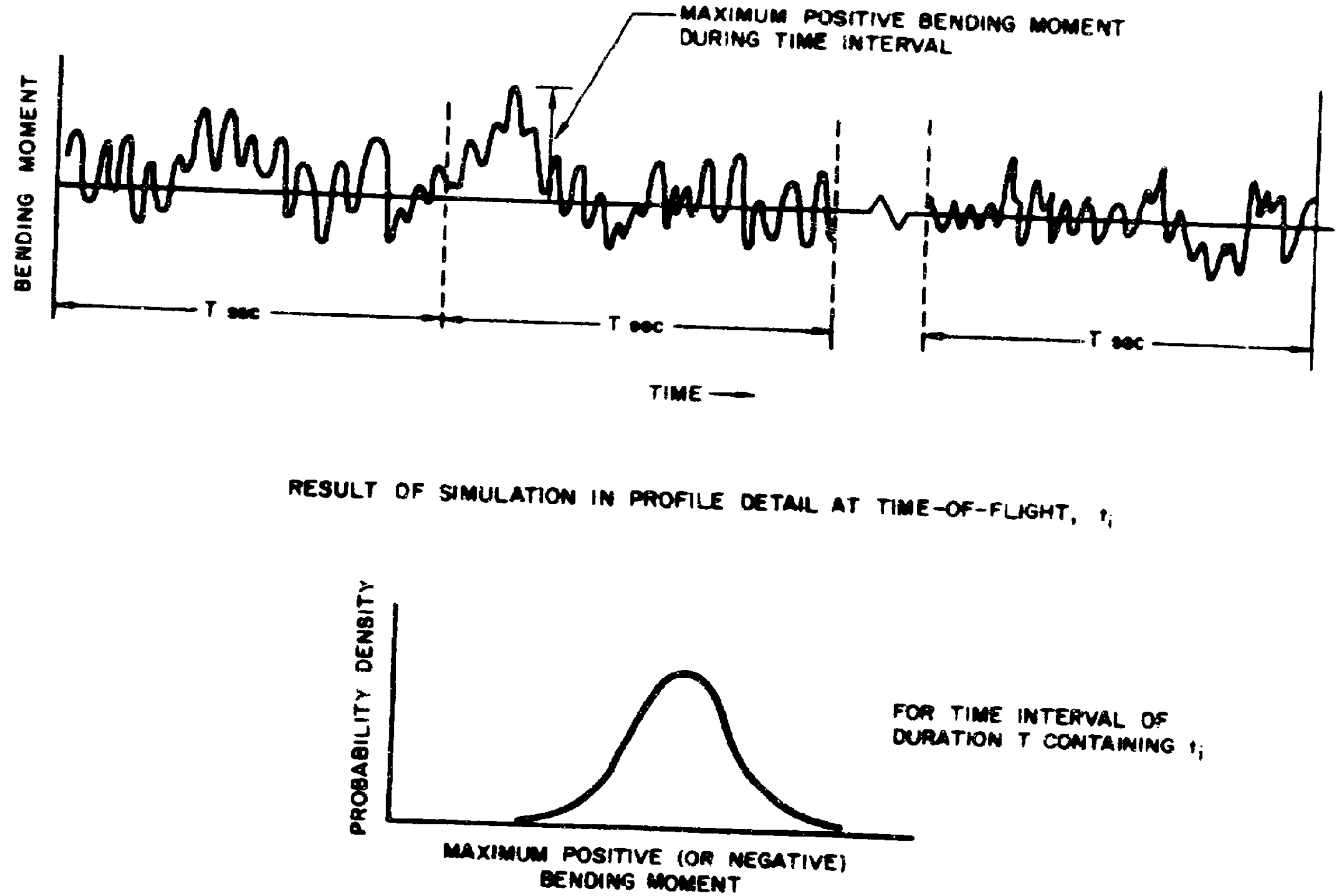
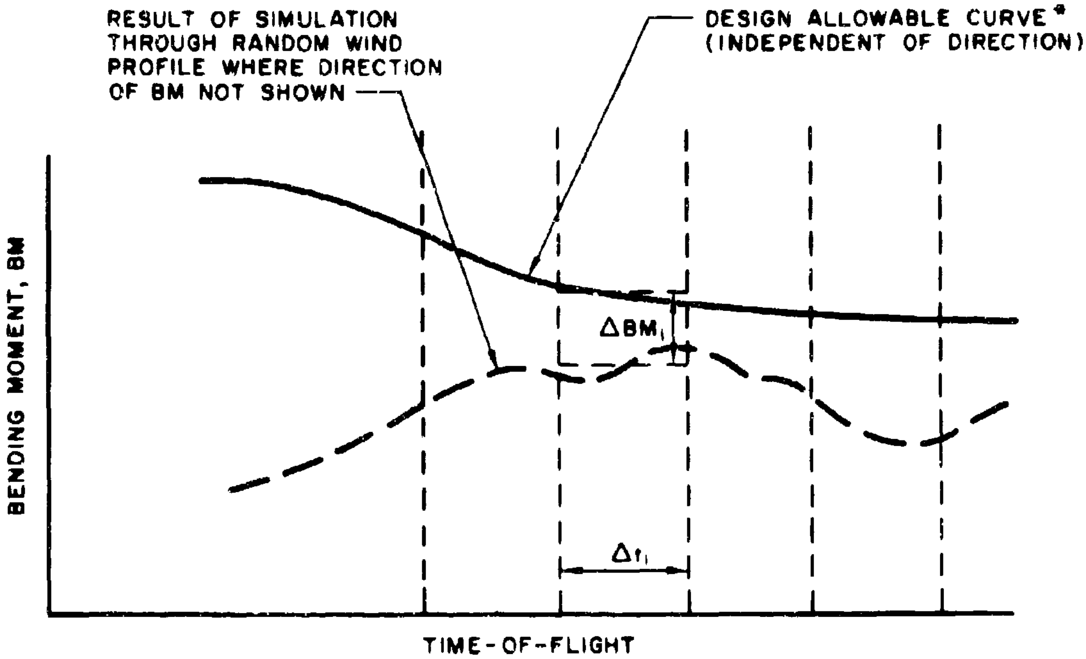


Figure 4. Obtaining Statistics of Structural Loads Caused by Profile Detail



*AXIAL LOADS SUBTRACTED AND SYMMETRICAL VEHICLE ASSUMED

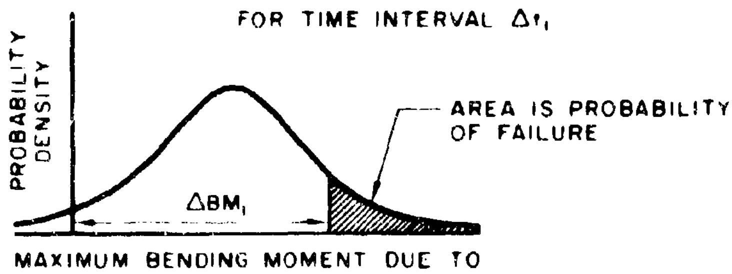
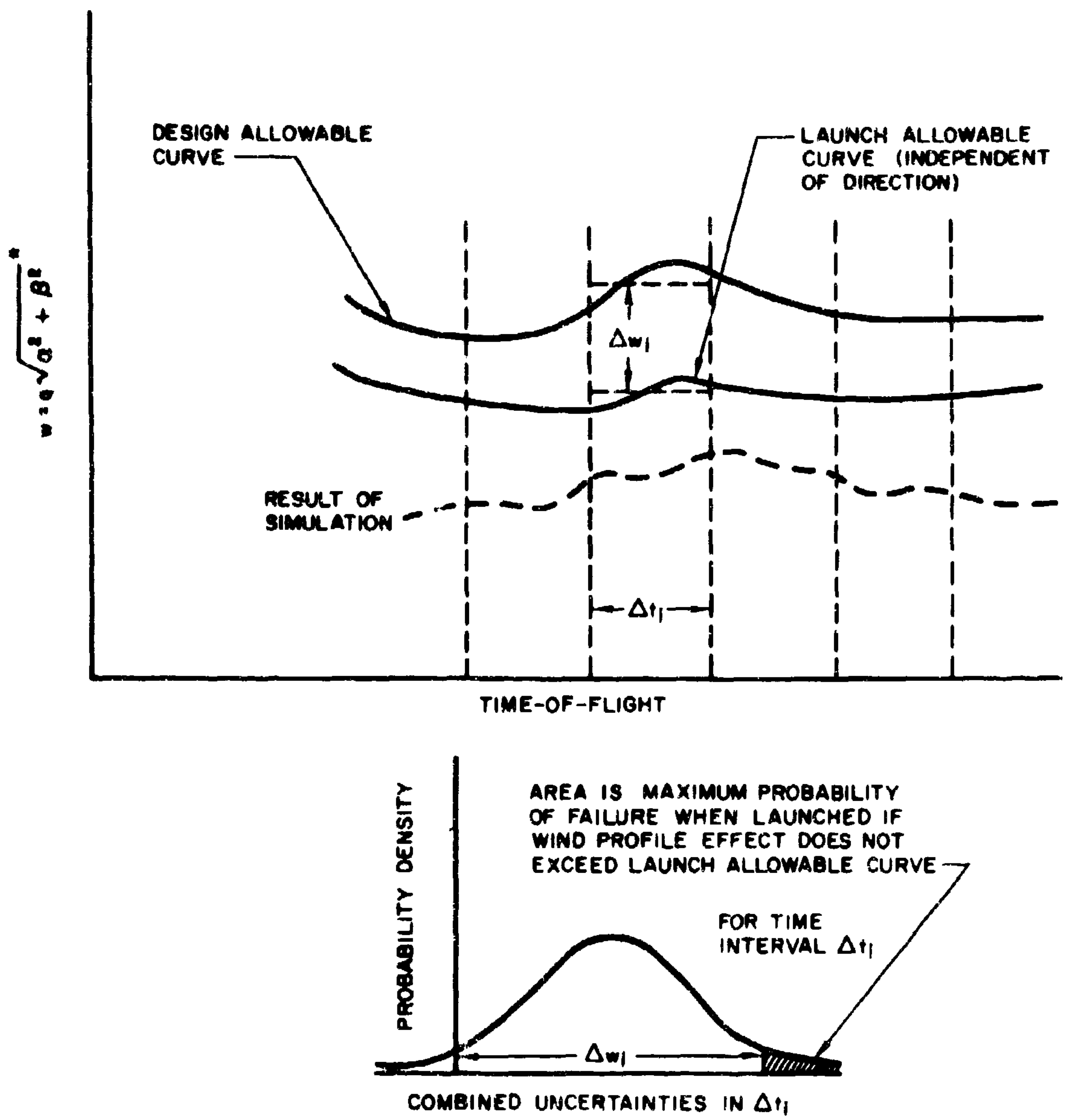


Figure 5. Graphical Solution of Probability of Structural Failure

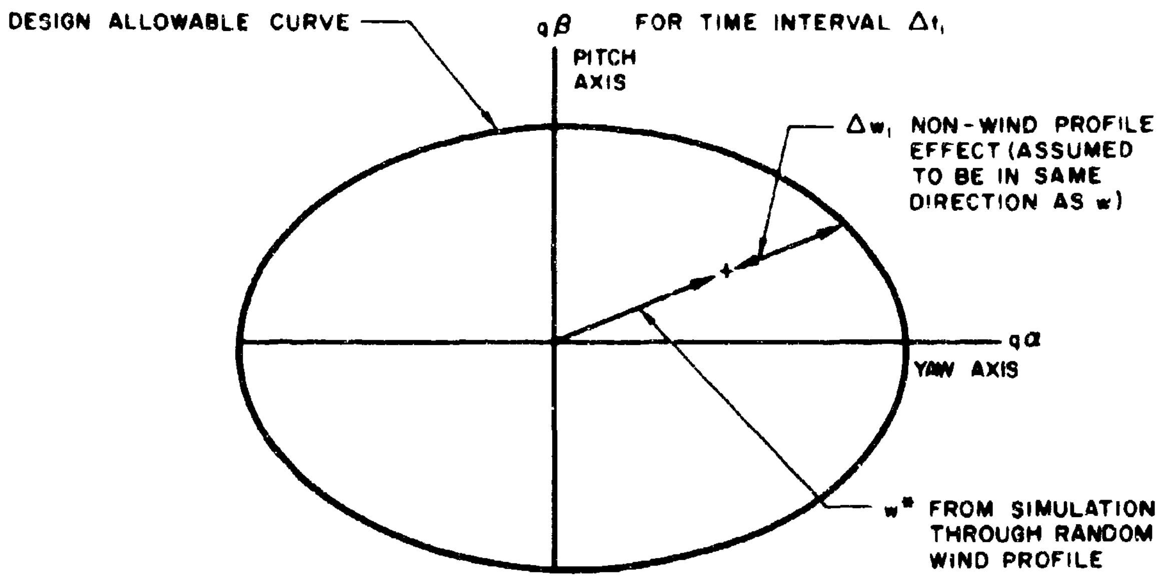


* q IS DYNAMIC PRESSURE

α IS ANGLE OF ATTACK

β IS SIDESLIP ANGLE

Figure 6. Graphical Solution of Launch Allowable Curve



$$^{*}w = q\sqrt{\alpha^2 + \beta^2}$$

WHERE, q = DYNAMIC PRESSURE
α = ANGLE-OF-ATTACK
β = SIDE-SLIP ANGLE

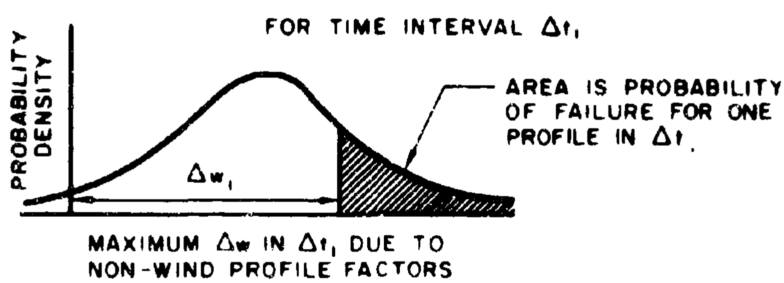
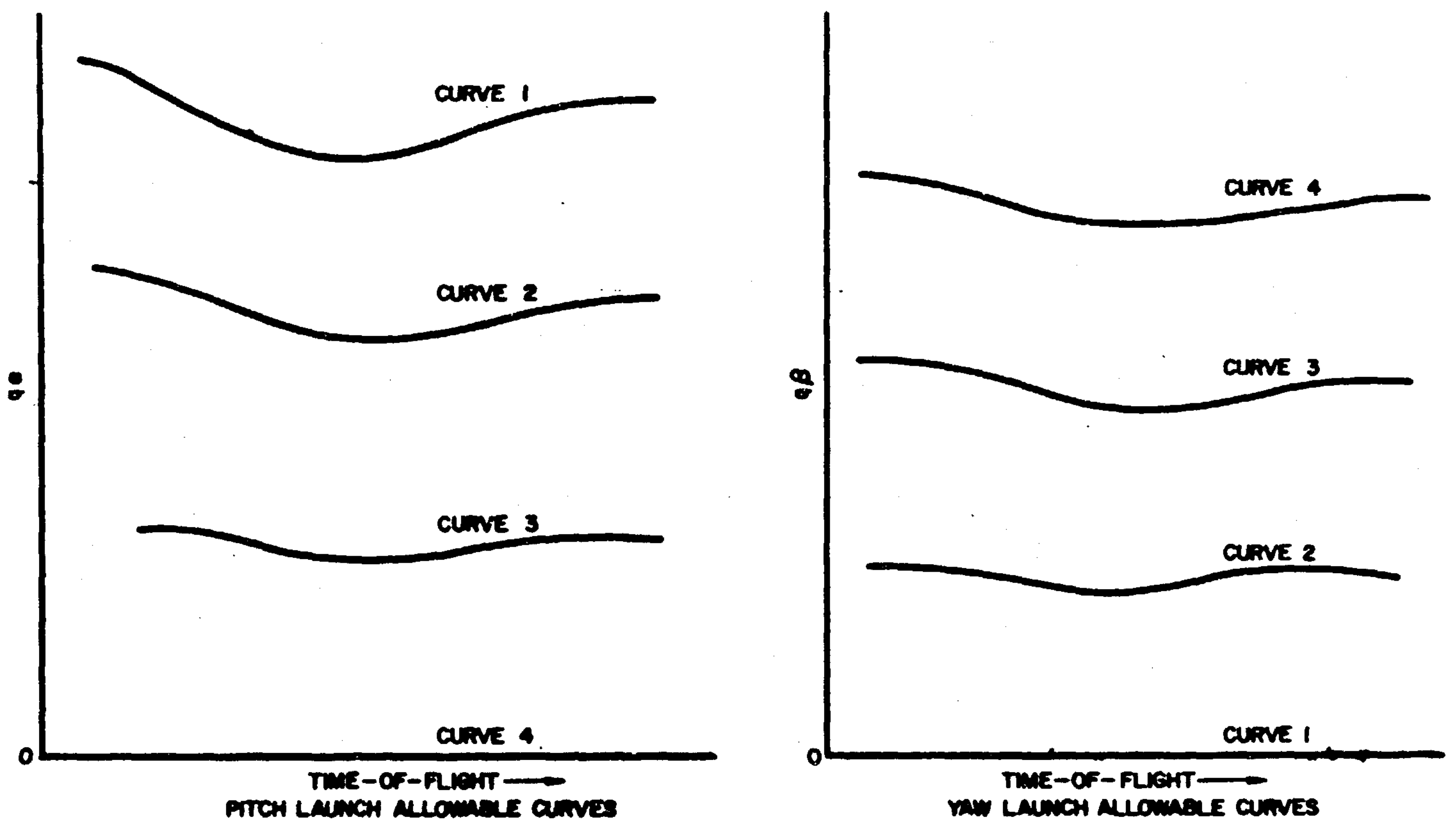


Figure 7. Graphical Solution of Probability of Structural Failure for Unsymmetrical Vehicle

TO USE CURVES: THE STRUCTURAL LAUNCH ALLOWABLE CURVE IS EXCEEDED IF, AT ANY GIVEN ALTITUDE:
(1) CURVE 1 IN PITCH OR CURVE 4 IN YAW IS EXCEEDED,
OR
(2) IF $q\beta$ IS ON A HIGHER NUMBERED CURVE THAN $q\alpha$. (MORE CURVES CAN BE OBTAINED BY INTERPOLATION FOR MORE ACCURACY.)



NOTE: FOR A SYMMETRICAL VEHICLE, CURVE 1 EQUALS CURVE 4, ETC.

DEFINITIONS: q IS DYNAMIC PRESSURE
α IS ANGLE-OF-ATTACK
β IS SIDESLIP ANGLE

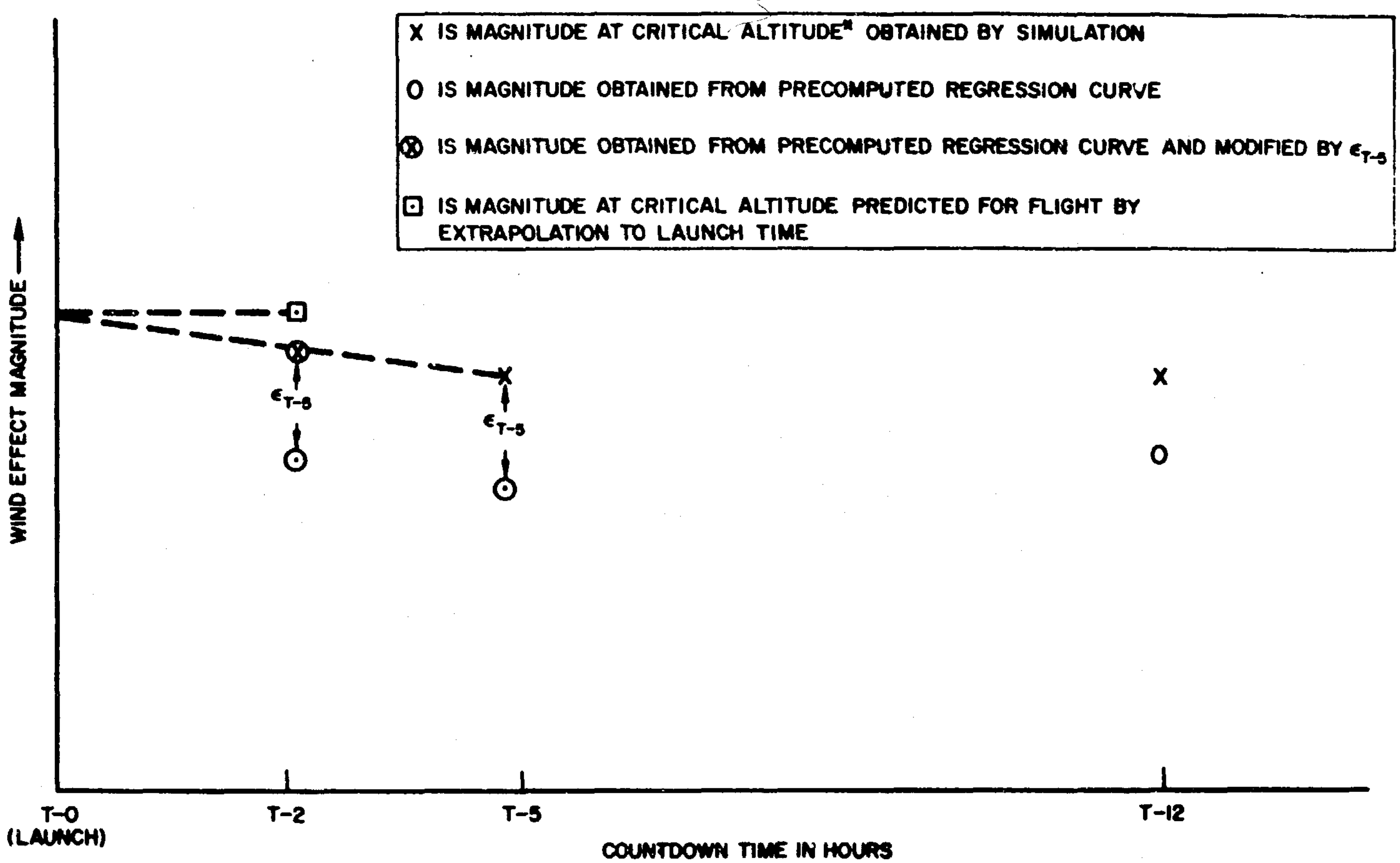
Figure 8. Structural Launch Allowable Curves for Unsymmetrical Missile

A WIND CHECK SCHEDULE

Meteorological Operation	Approx. Time Balloon is at Critical Altitude	Maximum Necessary Altitude	Wind Data Available	Method of Wind Effect Prediction	Wind Effect Predictions Completed
T-2 Day Prediction	-	60 K Ft.	T-40 hrs.	Simulation	T-36 hrs.
T-1 Day Prediction	-	60 K Ft.	T-16 hrs.	Simulation	T-10 hrs.
T-12 Hour Prediction	-	60 K Ft.	T-7 hrs.	Simulation	T-5 hrs.
T-5 1/2* Hour Sounding	T-5 hours	60 K Ft.	T-3 1/2 hrs.	Simulation	T-2 1/2 hrs.
T-2 1/2* Hour Sounding	T-2 hours	40 K Ft.	T-1 hrs.	Precomputed graph plus T-5 prediction	T-3/4 hrs.
T-0* Hour Sounding	T + 1/2 hour	60 K Ft.	T+6 hrs.	Simulation	T+1 Day

* Times of balloon release

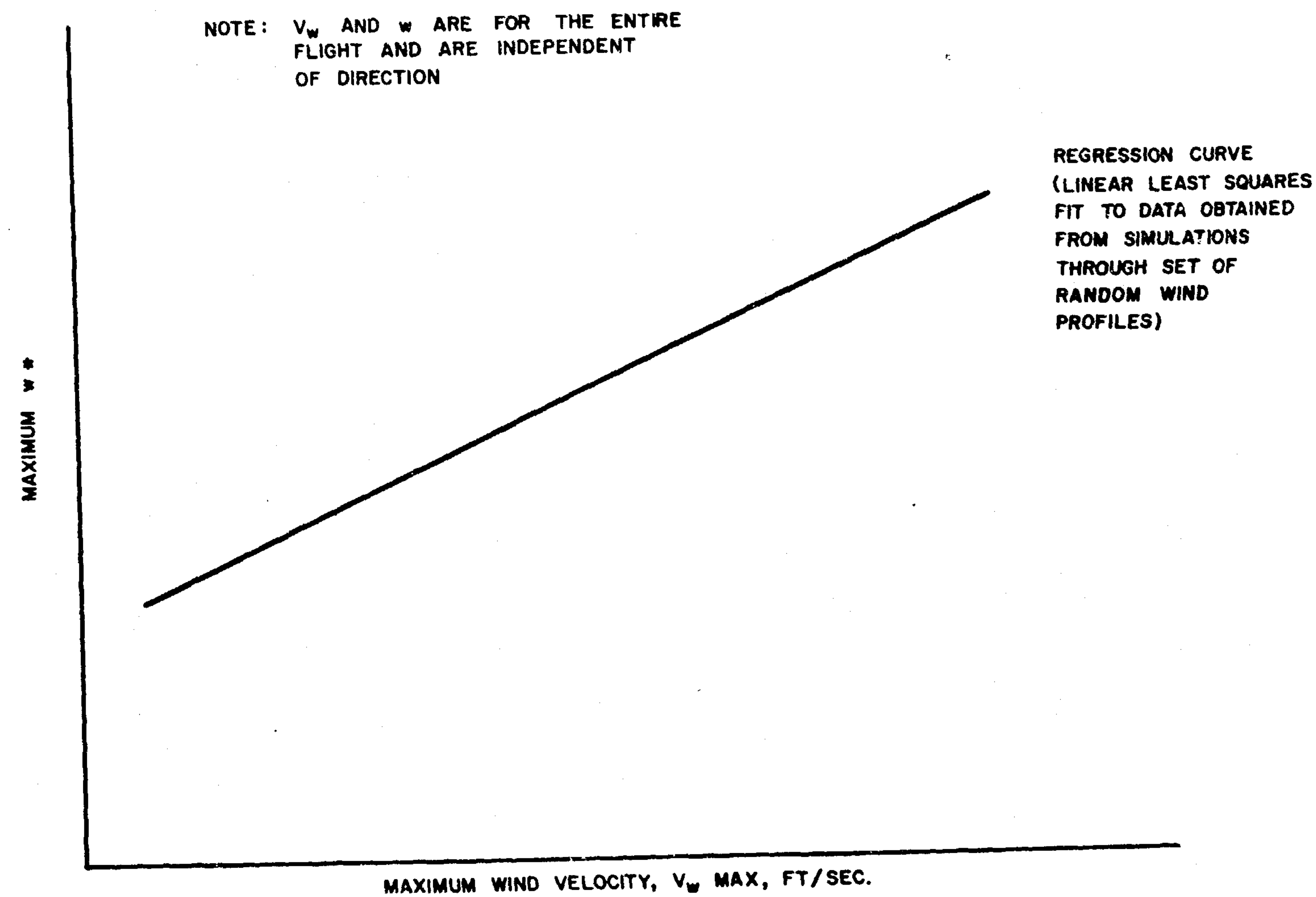
Figure 9. A Wind Check Schedule



NOTE: T-5 AND T-2 ARE THE APPROXIMATE TIMES THAT THE SCHEDULED T-5 1/2 AND T-2 1/2 HOUR BALLOONS REACH THE ALTITUDES OF HIGHEST WINDS.

* CRITICAL ALTITUDE HERE REFERS TO THE ALTITUDE AT WHICH THE COMPUTED WIND EFFECT MAGNITUDE IS CLOSEST TO THE ALLOWABLE MAGNITUDE.

Figure 10. Chart for Launch Decision



$* \; w = \left[(q\alpha)^2 + (q\beta)^2\right]^{\frac{1}{2}}$

Figure 11. Regression of Structural Load Versus Wind Velocity

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Aerospace Corporation, El Segundo, California. MISSILE DESIGN FOR THE EFFECTS OF WINDS ALOFT, prepared by D. C. Bakeman. 13 September 1962. [ ]p. incl. illus. (Report TDR-69(2116)TN-1; DCAS-TDR-62-190) (Contract AF 04(695)-69) Unclassified report

A major problem in the design of large booster missiles is the proper consideration of the effects from winds aloft. Since wind magnitude and direction are statistical in nature, the problem can only be solved by the use of statistical techniques. This report suggests that the design requirement be a given probability of failure or launch delay due to winds aloft, or an optimization between cost (in terms of weight, schedules, etc.) and the probability of failure or launch delay. A methodology is then presented, along with pertinent background information and discussion, for designing to any of those requirements. Also presented is a procedure (over)

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for a prelaunch wind check in which wind effects magnitudes are predicted for a flight.

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